A New Methodology for Design and Evaluation of Heterarchical Structures

Georgiy M. Levchuk[1]
Feili Yu[2]
Yuri Levchuk[1]
Krishna R. Pattipati[2]

[1]**Aptima, Inc.**
[2]**University of Connecticut**

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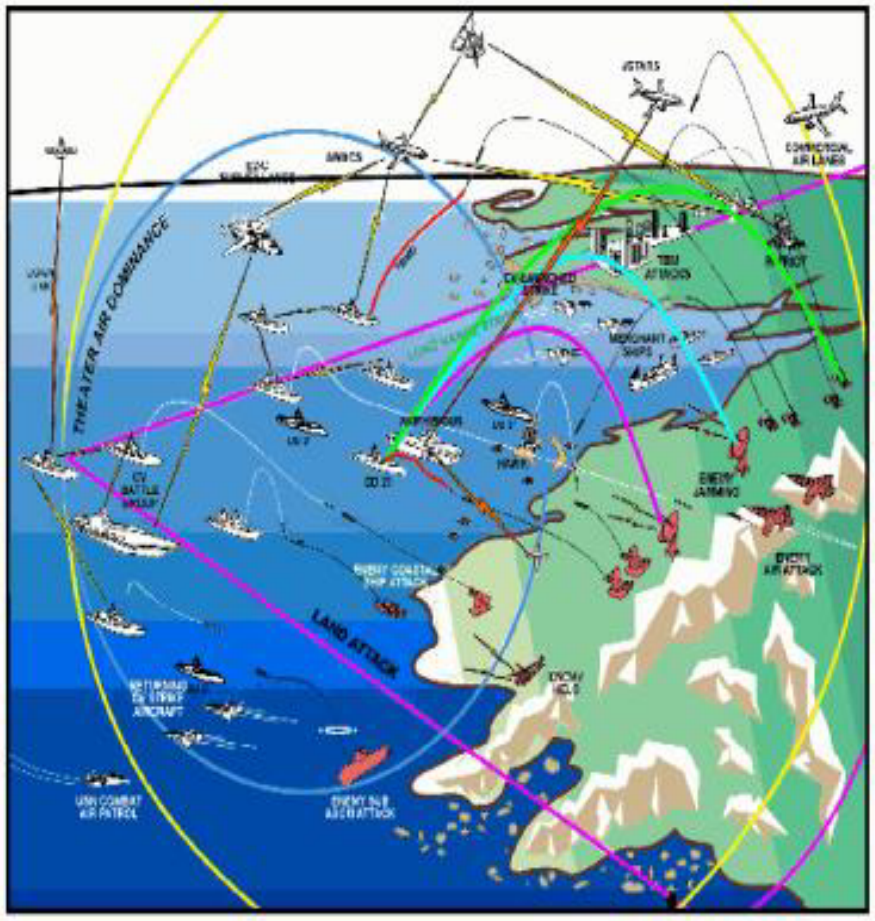
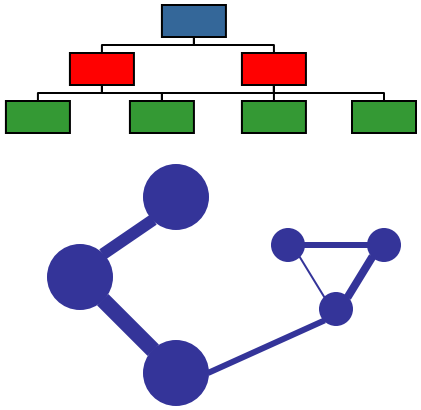
Basic Notions

- Mission
  - Events, activities, tasks to be executed
- Organization
  - Agents
    - Limited workload capacity
    - Heterogeneity in effectiveness of observation, command, information fusion, task execution
  - Structure
    - *Access* to and *transfer* of **resources**
    - *Access* to and *transfer* of **information**
    - *Generation* and *transfer* of **command**
    - Structures have **capacity** constraints
  - Strategy
    - Observation (who sees what)
    - Information routing and fusion (who communicates to whom)
    - Command execution and transfer (who commands whom)
    - Task allocation and execution (who executes what)
  - Resources

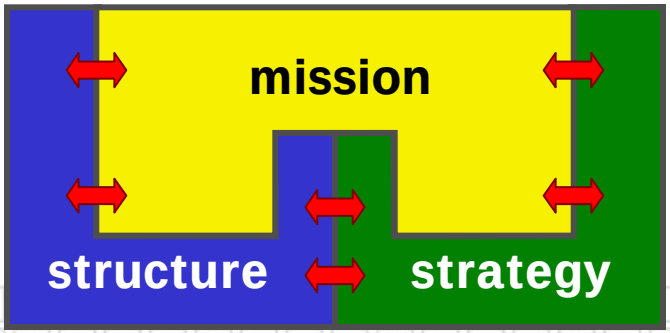


Formalization

- What problem are we addressing?
  - Design of organizational structures / networks and strategies
- What is the **structure/network** in our context?
  - Collection of items and rules/constraints of their interactions
  - Collection of nodes, links, channels



- What is the **strategy**?
  - Policy/procedures/rules/guidance to execute a mission
- What is an **issue**?
  - Interactions between mission, structure, and strategy



Overview

- Why study heterarchies?
- Types of Structures and Design Challenges
- Research evolution
- Problem identification & constraints
- Process chain
- Agent process graph
- Multi-layer network structure
- Solution approach
- Simulation examples

Why Study Heterarchies?

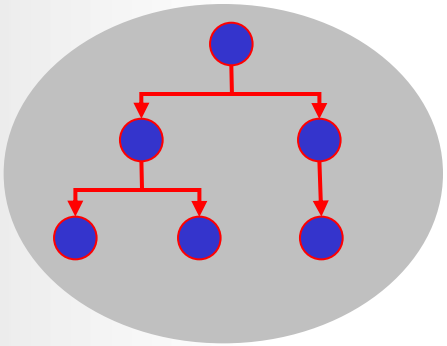
- New technologies – additional **friendly** flexibility to exploit (FORCEnet concept)
- Need to study the **enemy** (e.g., terrorist networks)
- Need to study the **environment** (e.g., customer networks, social interactive environments, supply-demand chains, "informal" relationships within hierarchies)
- Heterarchical relationships are "**richer**", and contain principles and mechanisms that have potential to render *superior performance*
- Thus need to study these relationships in order to:
  - determine how to **influence** other organizations
  - see if concomitant design principles can be **imbedded** into control structures of organizations to *enhance performance*

Types of Structures

Command

send commands

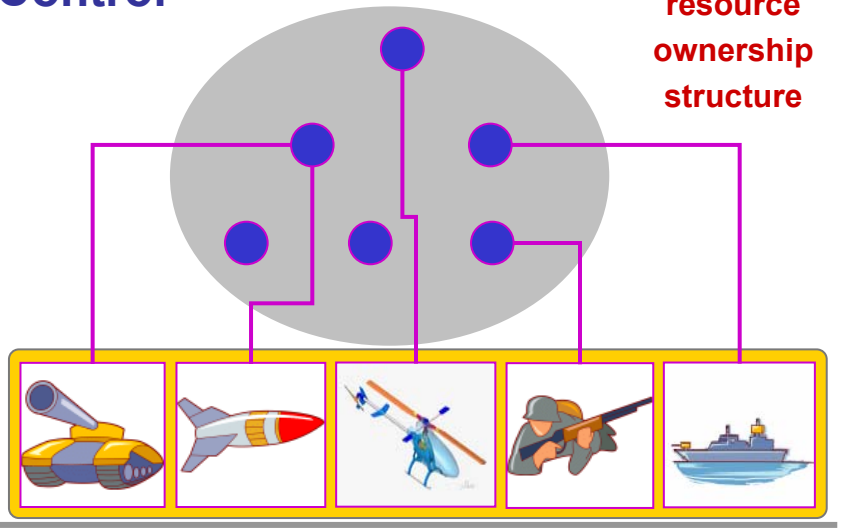
Execution ordering



Control

resource ownership structure

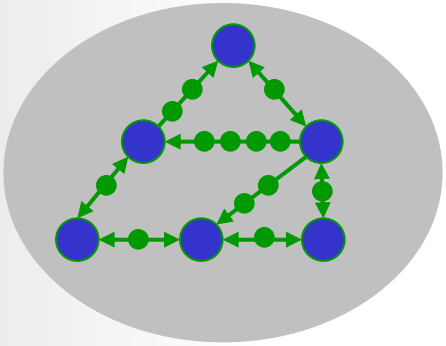
Execution capabilities



Communication

send information

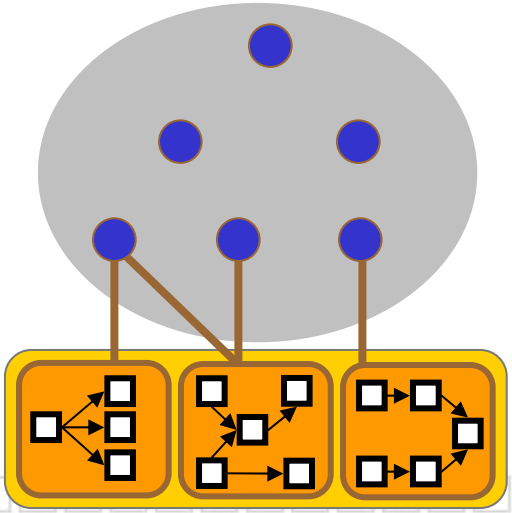
Info propagation



Information

info/event access structure

Knowledge/SA



Design Challenges

Challenge 1: Identification of interactions between agents

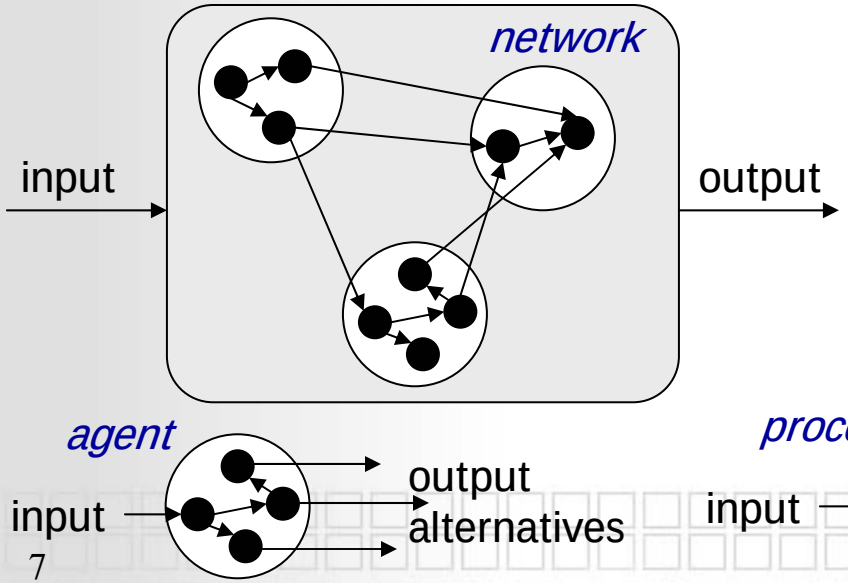
- Use template interaction message library
- Use rule-based reasoning in synthetic environment

Challenge 2: Interaction constraints and agent effectiveness

- Study restrictions in information access and flow, workload capacity, processing speed, command flow, etc.
- Study feasibility of structures in military domain

Challenge 3: Complexity & influence of (sub)structures and strategies on each other

- Model how flow is treated in the organization (transfer, consumption, generation, etc.)
- Inter- and intra-agent networks



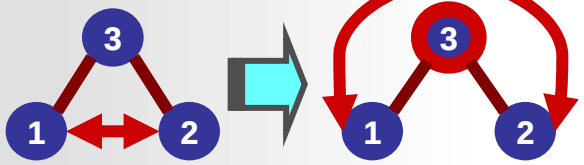
Modeling approaches:

- Use flow model: cost and capacity constraints
- Non-linear function of cost for flow transfer links
- Multi-commodity & non-splittable flow modeling
- Heuristic algorithms to maintain network robustness
- Local / distributed decision making

Research Evolution

Overhead-based design

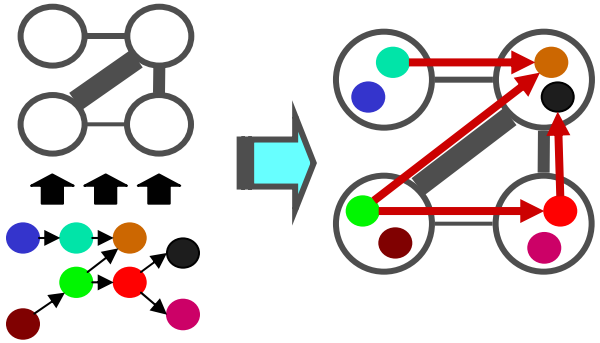
- *Given:* **communication requirements**
- *Find:* a **hierarchy**
- *Objective:* minimize **communication overhead**
  - Based on exceptions to process, decision-making workload, and load of information transfer



Cons:
- No **effect** of overhead
- No network constraints

Schedule-based design

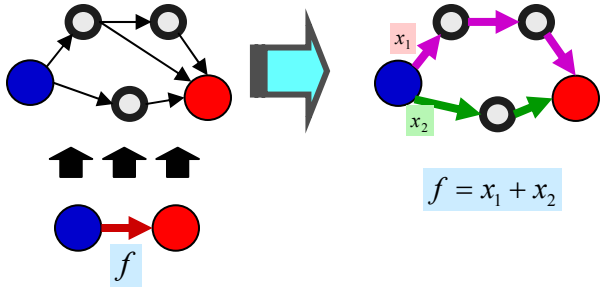
- *Given:* **agent network**
- *Find:* a **task assignment** and **schedule**
- *Objective:* minimize **mission time**
  - Based task information flow and inter-agent communication



Cons:
- Global controller
- No network design
- Limited routing; no info split

Routing-based design

- *Given:* **communication requirements**
- *Find:* a **network** and **info routing**
- *Objective:* minimize **average delay**
  - Based on information routing & queuing model



Cons:
- No strategy (assignment)-structure allocation
- No multi-structure design

Design Evolution

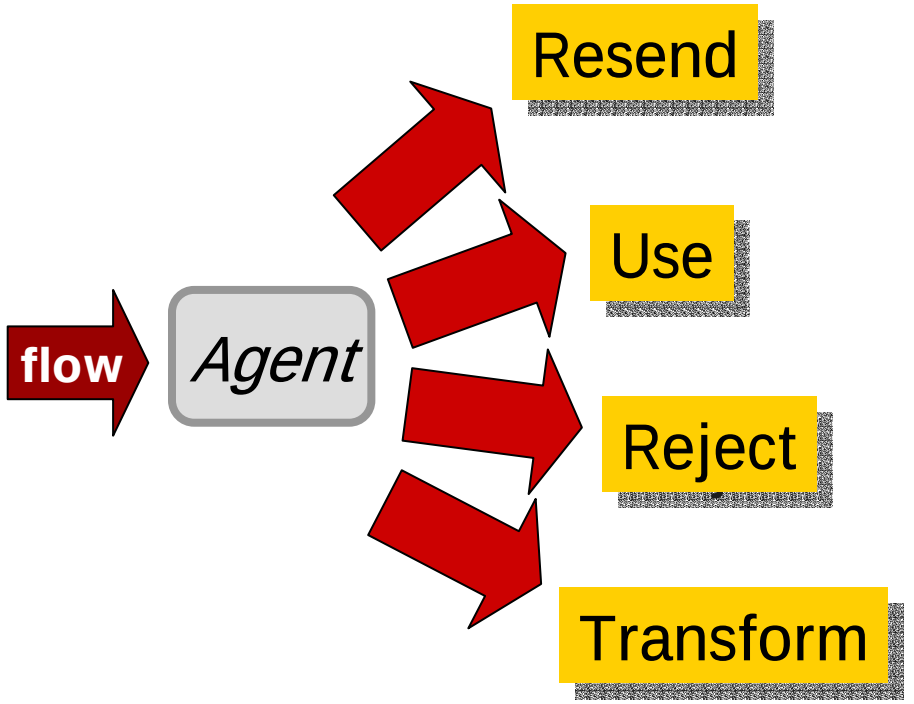
What is Missing?

- Strategy-structure-mission interaction/influence

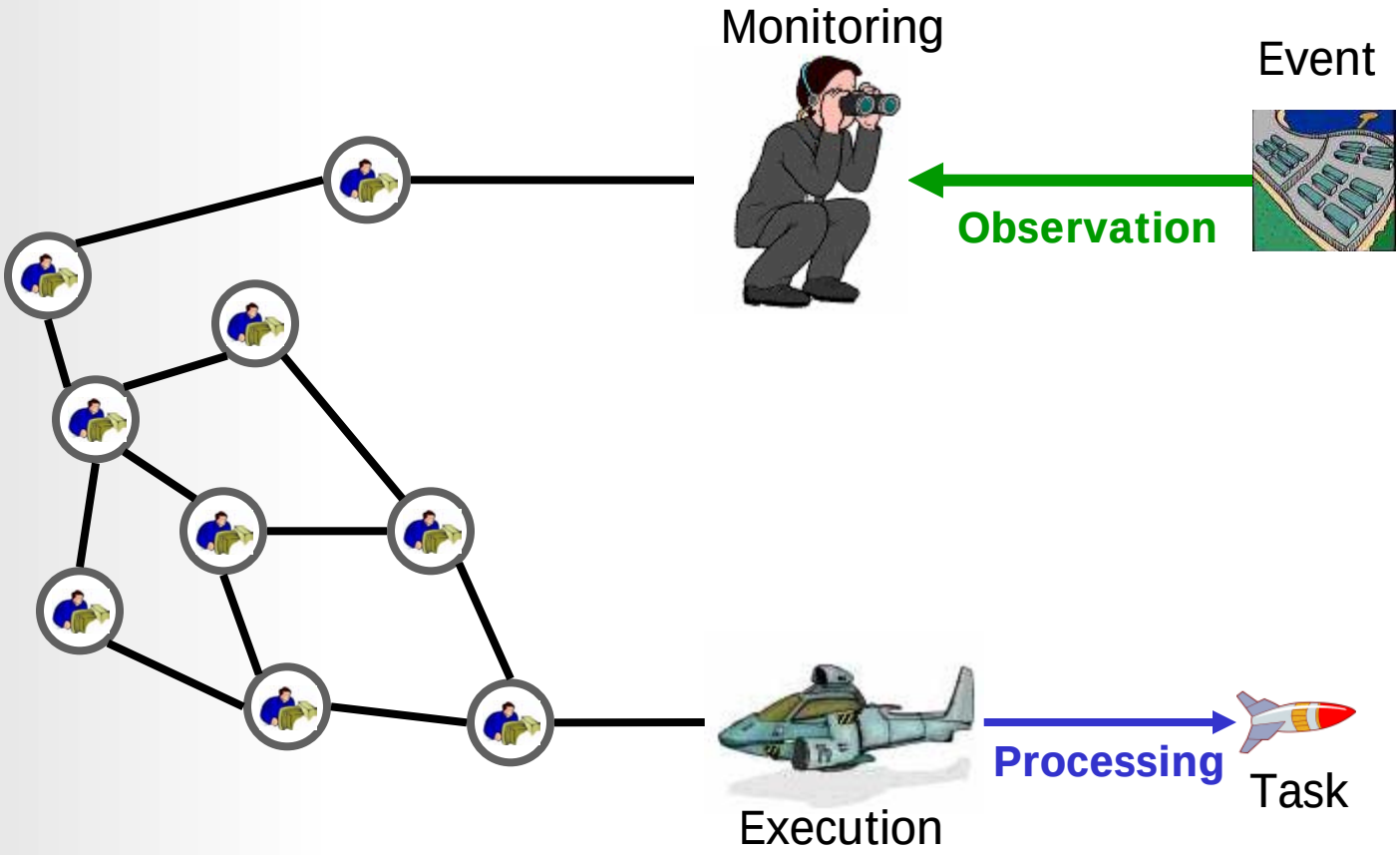
- **Strategy:** how and what is done
- **Structure:** by what means a strategy is accomplished
- **Mission:** what needs to be accomplished

Problem Identification

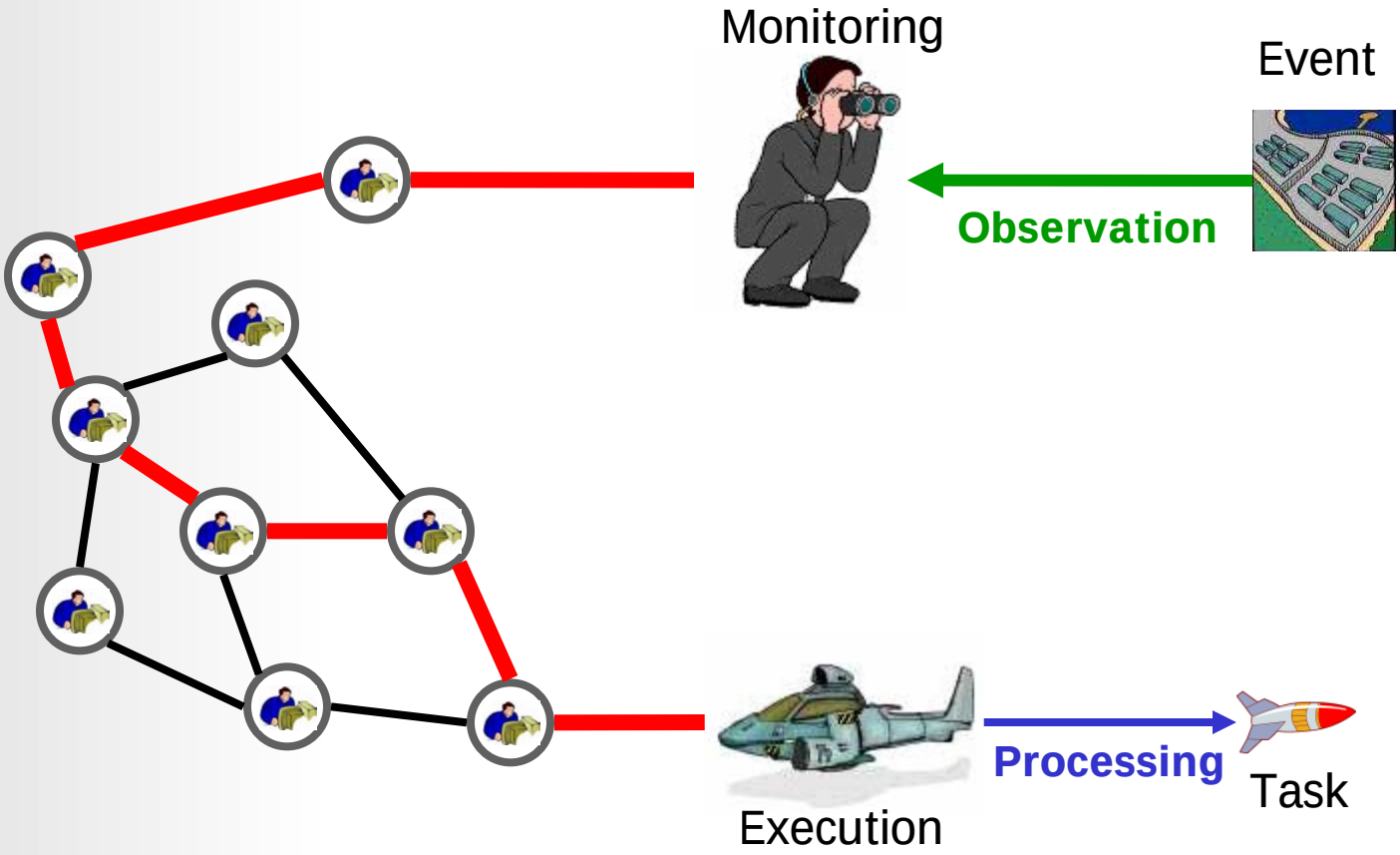
- Agents
  - Observe events
  - Receive/transfer/fuse info
  - Generate/receive/transfer command
  - Receive/transfer/process tasks
- Links/Channels
  - Transfer information
  - Direct command
  - Access observations
- Model agent operations as flow processing
  - Flow of information, command orders, resources, requests for synchronization, exceptions, etc.



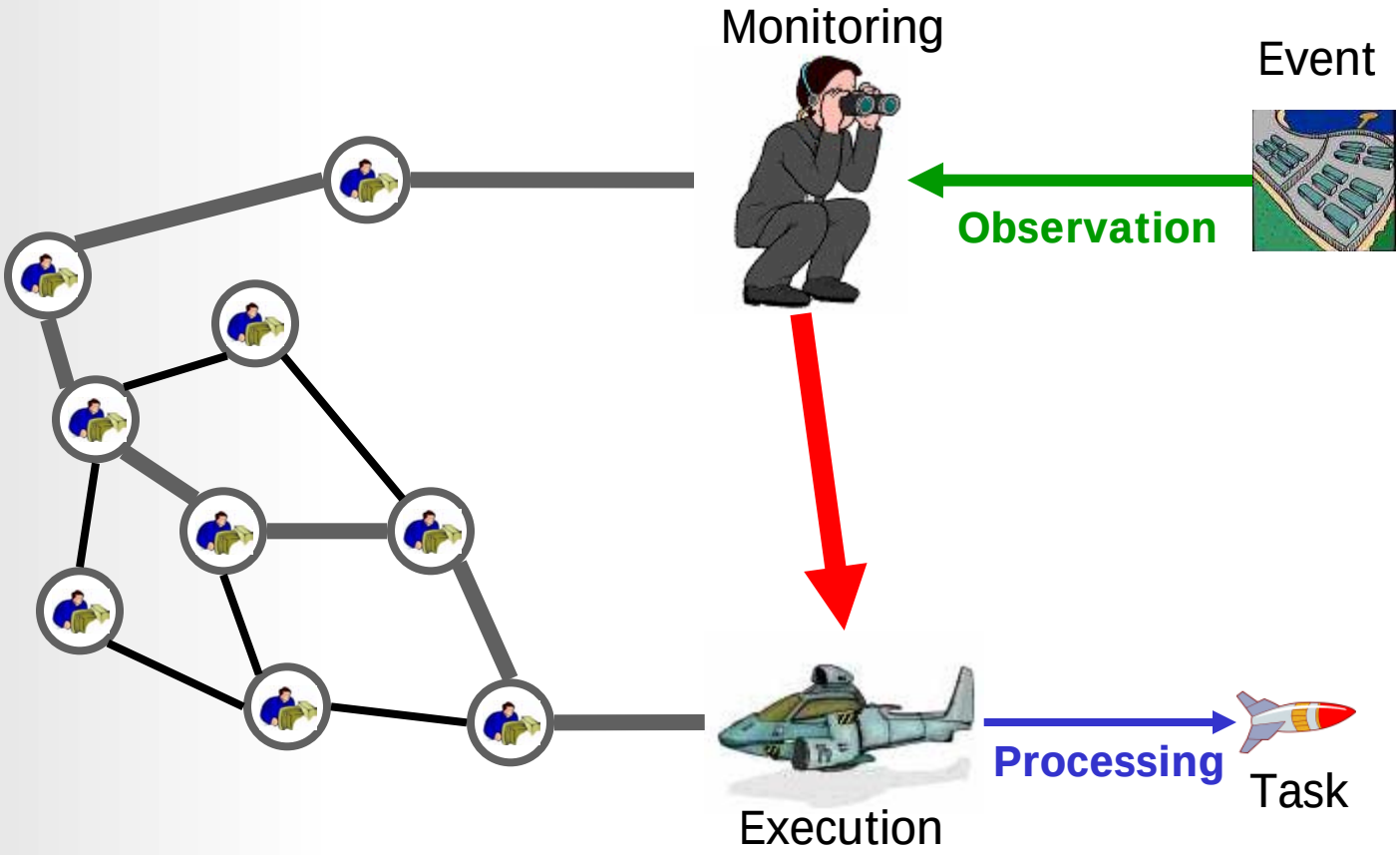
What Are We Doing?



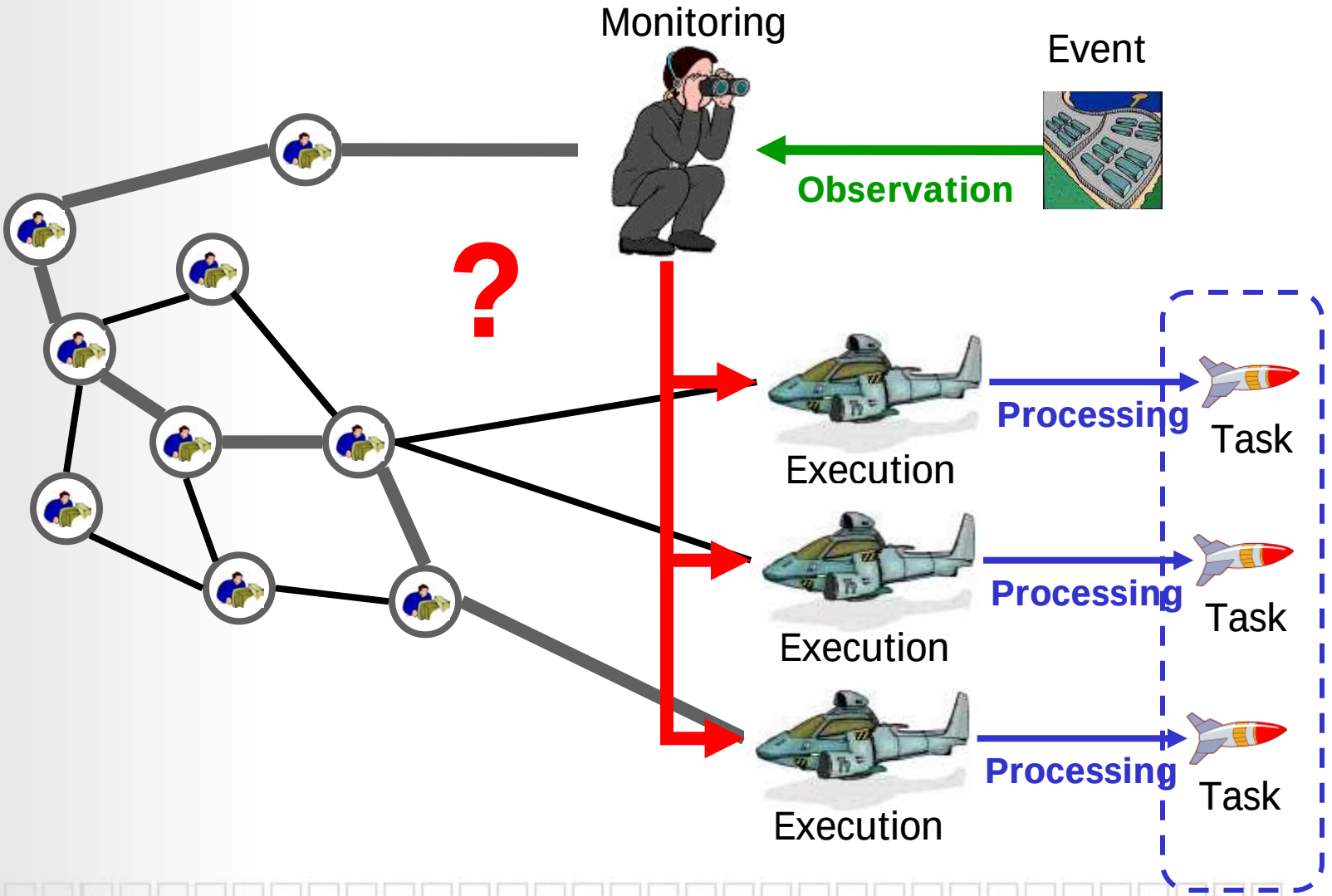
Getting the Right Info to Right People



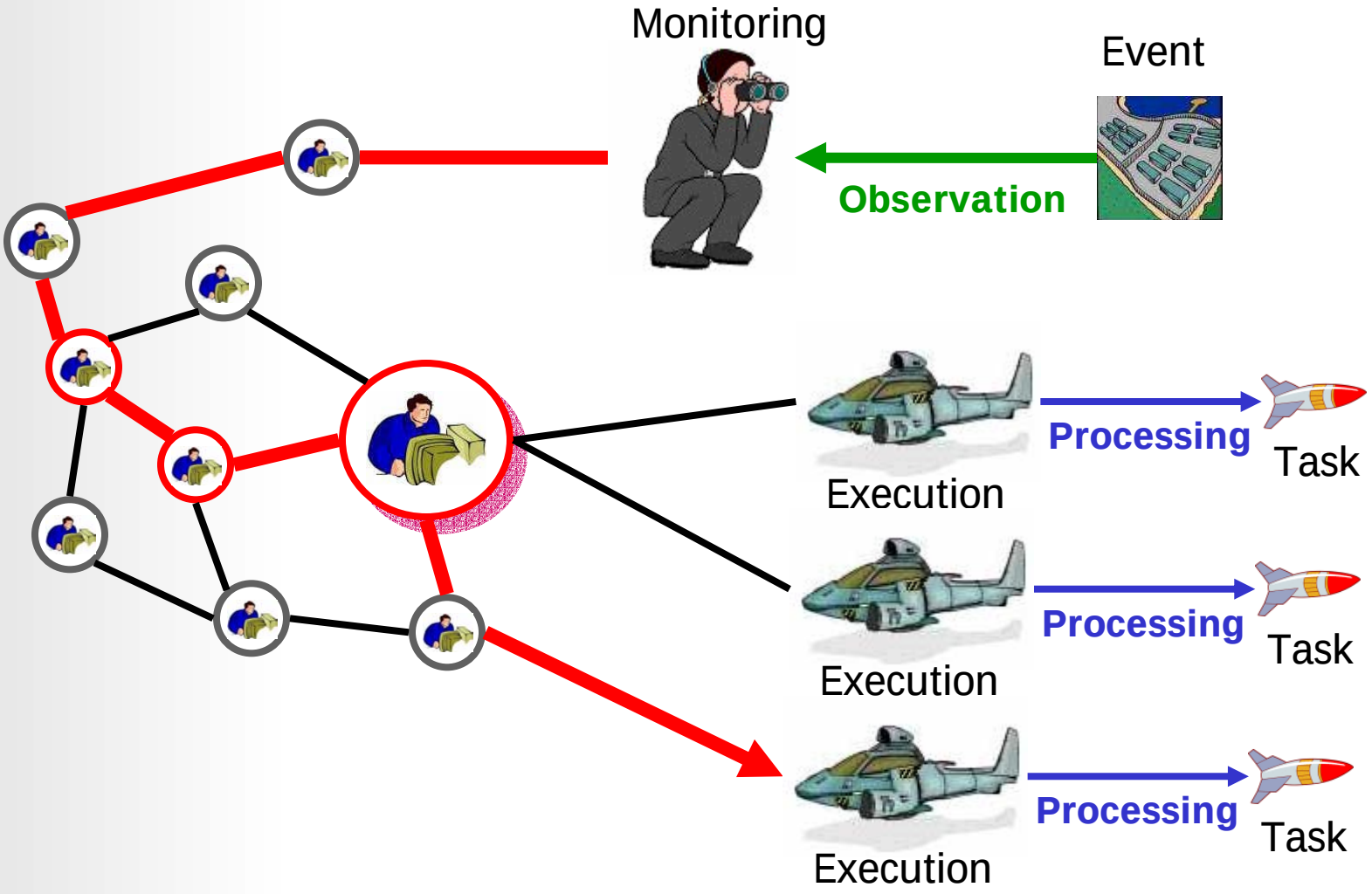
Direct Info Access



Info Conflict



Command as a Resolution



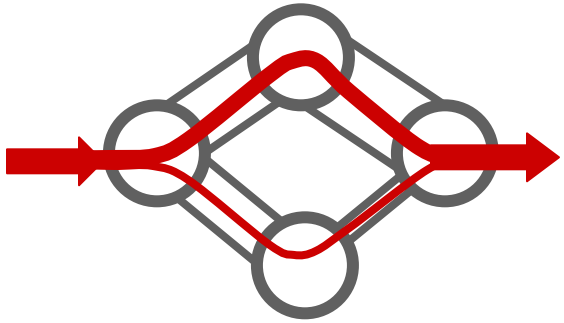
Constraints

- Agents:
  - Workload capacity
    - Limit amount of operational and cognitive load
    - Include load of observations, communication, decision-making, task execution
  - Operation efficiency
    - Different expertise for observation, command, task processing, transfer
    - Based on agent expertise
      - Multiple types of expertise assessed; grading each
      - Multi-type expertise capability ⇒ generalists
      - Single-type expertise capability ⇒ specialists
- Links/channels:
  - Cost of maintenance
  - Use simple linear function of flow amount

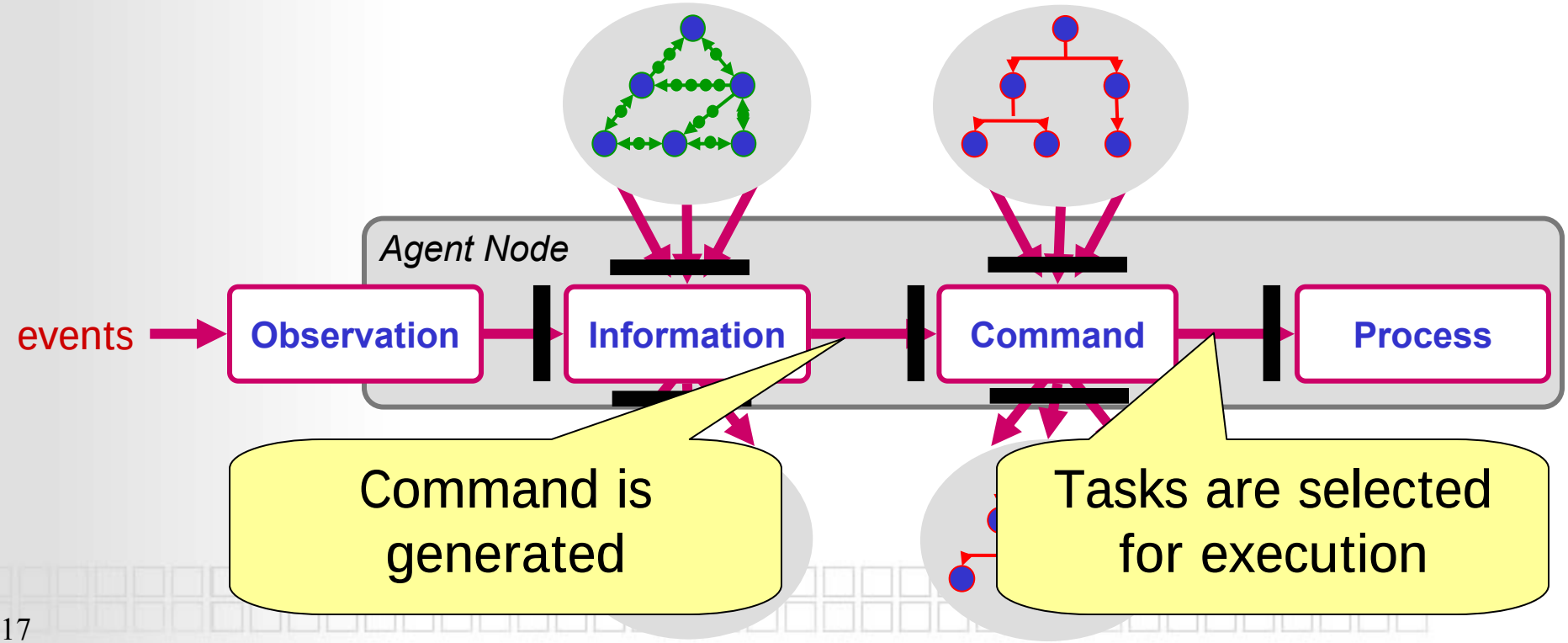
Problem Specifics

- Flow chain:

splitting allowed



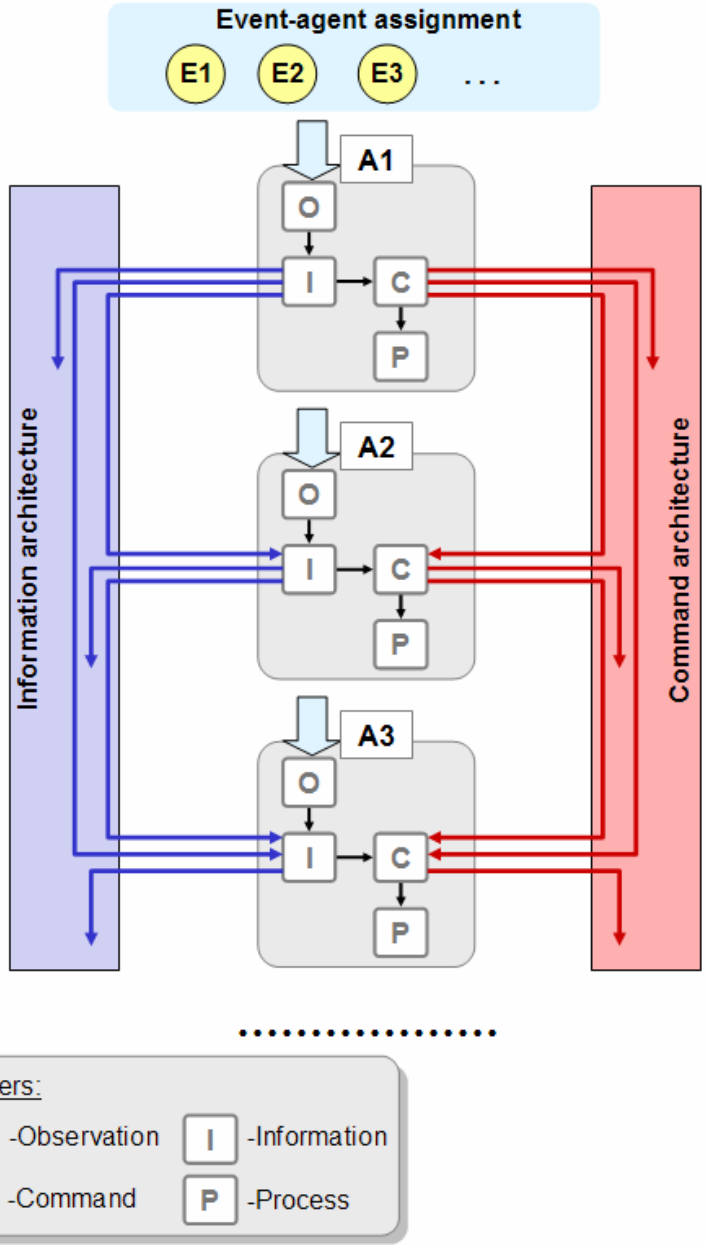
- Agent process graph:



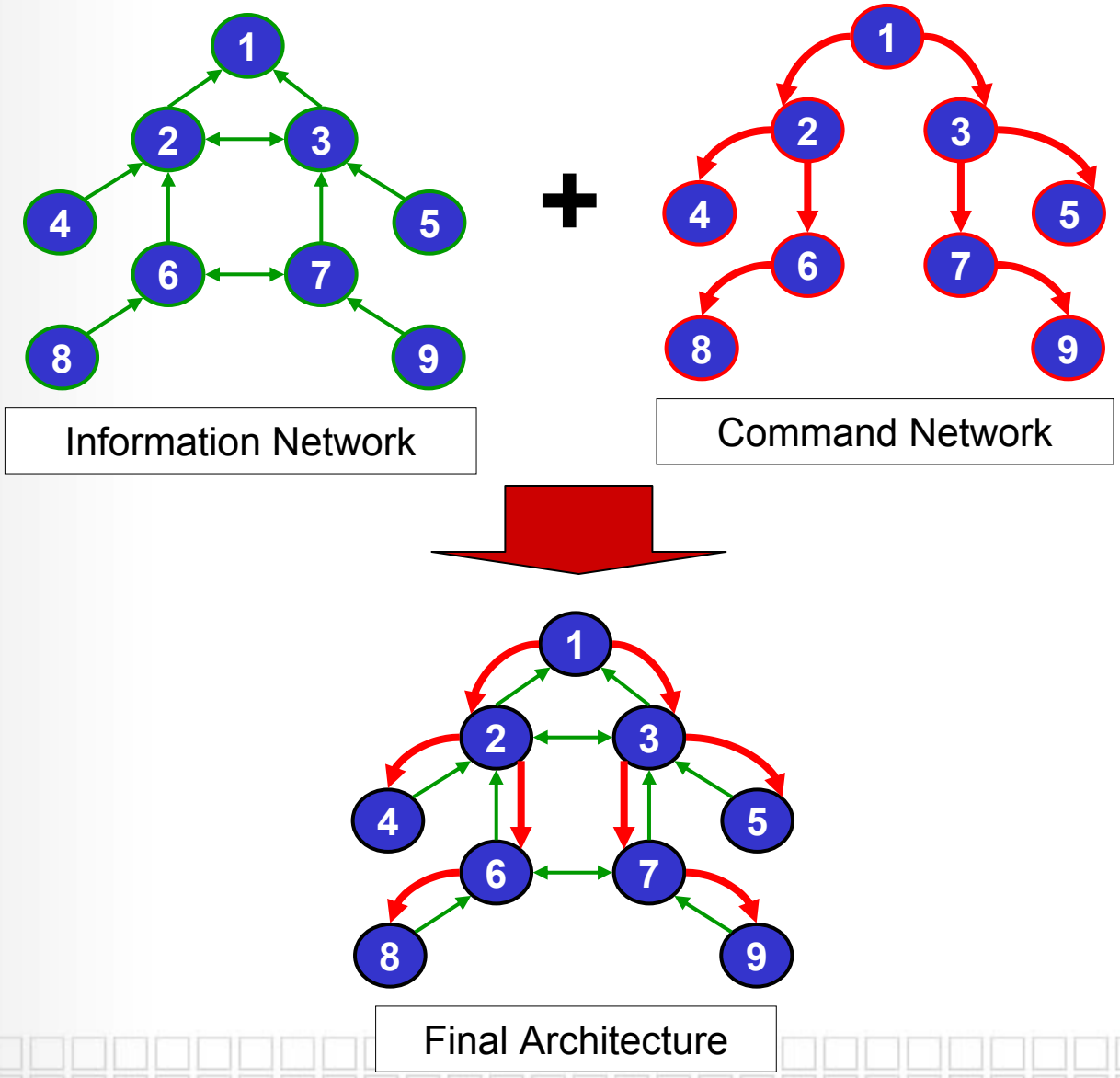
Capacity and Mission Gain

- Capacity
  - Identifies the threshold of volume
  - At agent process nodes & links: agents constraints
  - At links/channels: structure constraints
- Mission Gain
  - **Positive – task execution gain:** from the efficiency/accuracy of agents to observe, conduct decision making, execute tasks, communicate
  - **Negative – transfer cost:** info/tasking through network
    - Network maintenance
    - Information loss
    - Interpretation loss
    - Noisy transmission

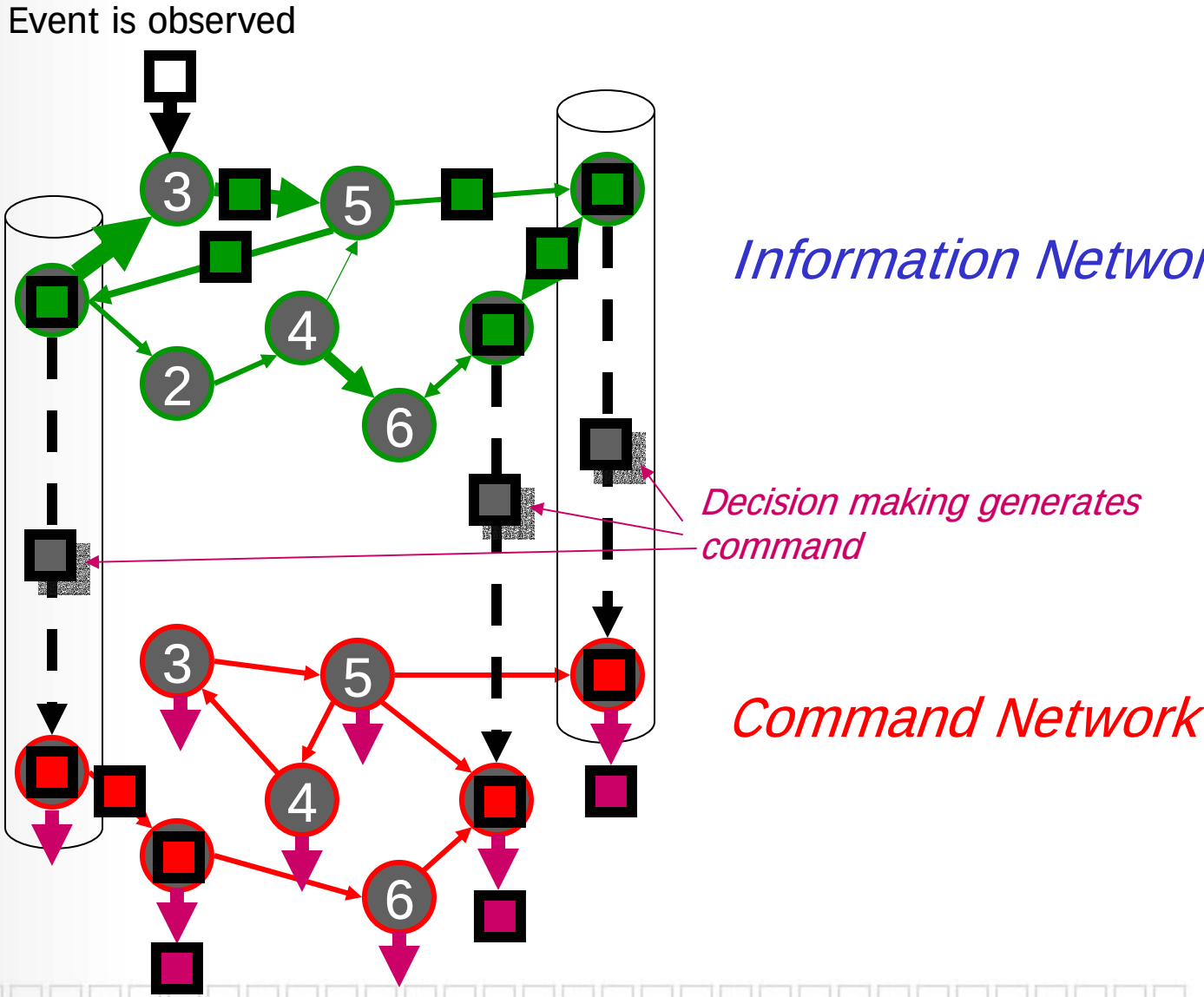
Joint Graph


Event-agent assignment
E1
E2
E3
. . .
A1
O
I
C
P
A2
O
I
C
P
A3
O
I
C
P
Information architecture
Command architecture
Buffers:
O -Observation
I -Information
C -Command
P -Process

Example of Hybrid Structure



Multi-Layer Organization



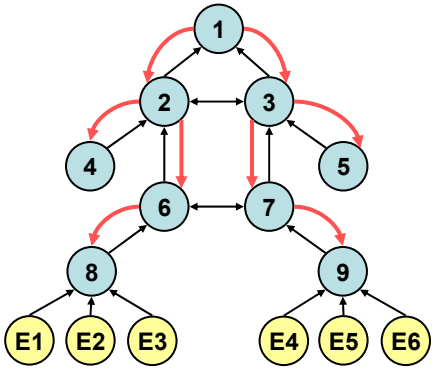
Solution Approach

- **Step 1:** Define mission
  - Events volume and expertise requirements
- **Step 2:** Define organization
  - Agent expertise
- **Step 3:** Define agents' process graphs
  - Agent capacities, processing gain
- **Step 4:** Define structure constraints
  - Link/channel capacities for different-type networks
- **Step 5:** Expand the aggregate network
  - Replace node capacity and gain constraints with link capacities and cost
- **Step 6:** Apply minimum cost maximum flow algorithm

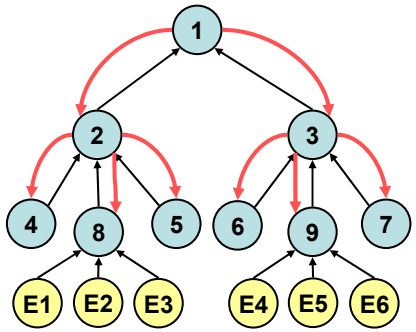
Output

- **Structure:** specification of load for sub-networks
  - Can use to design network bandwidth and architecture
- **Strategy:** specification of who does what
  - Observation, fusion, communication, transfer, execution

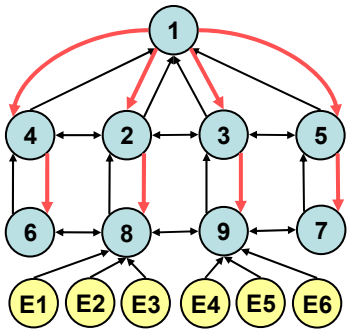
Sample Results



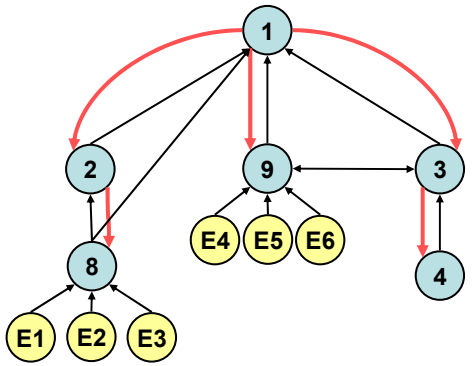
Structure **A**



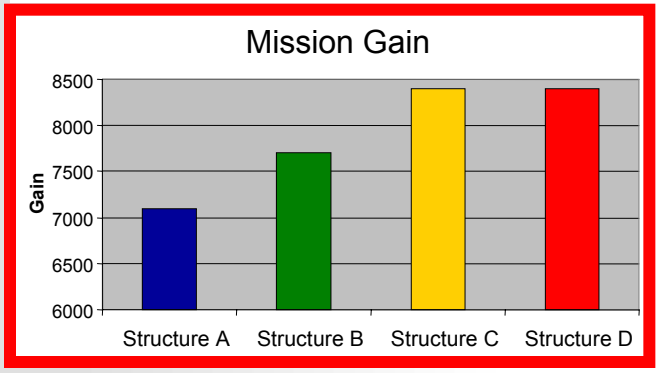
Structure **B**

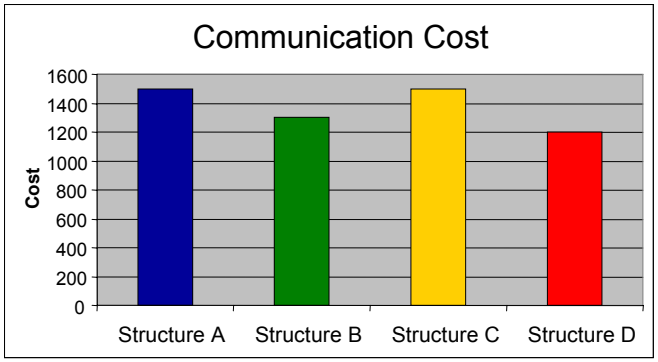


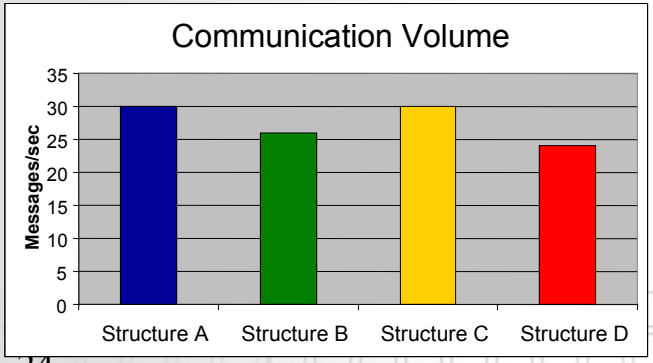
Structure **C**

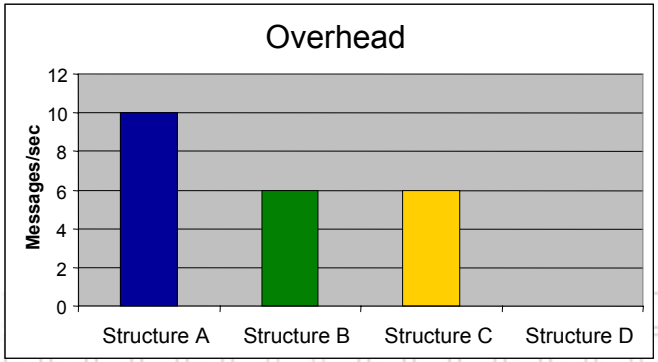


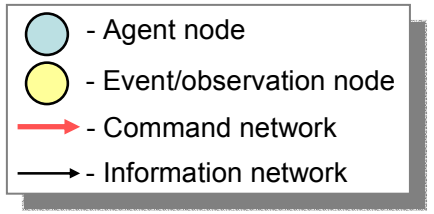
Structure **D**











- Increase the accumulated mission execution effectiveness (gain) while decreasing the communication overhead, cost and volume
- **Optimal network allows better access to efficient nodes**

Future Directions

- Consider network robustness constraints
- Implement **multi-commodity** problem formulation
  - Currently we implemented single-type events
- Consider problem of **unsplittable** or partially splittable flows
  - An item can only be transferred through **single path**, without splitting
- Consider flow **transfer** and generation
  - Flow volume change
- Consider error propagation
- Consider local autonomous agent strategy based on partial information

Conclusions

Accomplishments:

- Developed methodology to design inter-dependent organizational sub-structures (command, observation, communication, information)
- Utilize the benefits and constraints of hierarchical, heterarchical, and hybrid structures
- Integrated structure-strategy optimization

Applications:

- Will provide innovative strategy and structure solutions for various levels and nodes of the FORCEnet